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Review

Ambient air quality and exposure assessment study of the Gulf Cooperation Council countries: A critical review

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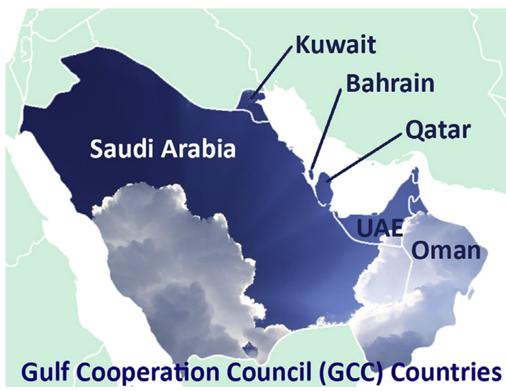
HIGHLIGHTS

- This review paper identifies the major sources of air pollutants in the GCC region.
- CO_2, CO, PM, metal elements, NO_x, O_3, SO_2, VOCs, PAHs, and POP were considered here.
- The exposure assessment of major air pollutants was reviewed.
- Sand, industrial chemicals and vehicles were the main contributors to air pollution.
- Oil and natural gas activities have also the most important impact in the region.

GRAPHICAL ABSTRACT



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ABSTRACT

With rapid urbanization and economic growth, many developing countries have faced a greater share of air pollutants in recent years. An increasing number of exposure studies on air pollutants have been reported lately. However, due to lack of strict regulations and monitoring stations among developing countries, such as Gulf Cooperation Council (GCC) countries, limited air pollution and exposure assessment studies have been conducted in this region. Thus, the objective of this critical review was to identify the major sources of air pollutants in the region with hot and arid/semiarid climate for the main categories contributing to specific pollutants. Finally, a summary of the limitations and knowledge gaps were discussed. Additionally, the current available regulations, emission inventories and source apportionment studies in this region were discussed. In this study, the concentration levels of carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), metal elements, nitrogen oxides (NO_x), ozone (O_3), sulfur dioxide (SO_2), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs) were reviewed. Due to lack of scientific studies, various databases and indexed journals from early 2000 (sometimes prior that time) were considered. The review findings clearly indicated that the sand, dust (natural and anthropogenic, such as cement, metal, stone cutting industries), chemical industries (refinery, petrochemical, etc.) and transportation activities were the major contributors to the overall air pollution in the GCC countries. Besides, the study recommended that the difference between anthropogenic pollution and natural events in dust formation should be explored extensively. Furthermore, possible suggestions for future researches in the region were proposed.

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Contents

1. Introduction

The environmental pollution is becoming more and more serious subject and a hot topic of debate in recent years. Currently, air pollution is named as one of the major issues affecting both the environment and human beings (Al-Salem and Bouhamrah, 2006; Al-Wahaibi and Zeka, 2015). Exposure to air pollutants leads to a variety of health effects, which is subjected to type, concentration level, duration, frequency, and associated toxicity of them (Cooke et al., 2007; Al-Wahaibi and Zeka, 2015). Age, cultural practices, living places, and lifestyle may influence the exposure to air pollutants as well. Therefore, the impacts of air pollutants and the severity of health outcomes in a given population depend on the population sensitivities and cannot be directly generalized from the results of other backgrounds.

According to the World Health Organization (WHO) report in 2014, one in eight of total global deaths (around 7 million people) died as a result of air pollution exposure. The number of death is more than double compared to previous estimates and confirms that air pollution is now the world's largest environmental health risk (WHO, 2014). Therefore, reducing air pollutants could save millions of lives every year. Unfortunately, due to lack of both awareness and proper regulations, air quality has been deteriorating progressively in developing countries (Abdul-Wahab, 2008). For example, air pollution was ranked as the major contributor to premature mortality in terms of risk priority in the United Arab Emirates (UAE) (Gibson and Farah, 2012).

Rapidly expanding economy, especially in developing countries, has a direct relationship with the environmental quality. As reported by Ebinger et al. (2011), the Gulf Cooperation Council (GCC) countries are likely to experience one of the most rapid growth rates in economic and energy consumption in the world over the next twenty years. During this period, oil and gas reserves are the primary causes of air pollution, which result in steadily deteriorating of air quality in this region (Al-Ghamdi et al., 2015). Furthermore, distribution of the air pollutants in this region is strongly affected by the major seasonal sandstorms (Brown et al., 2008; Meo et al., 2013). To address air pollution and other environmental challenges in the GCC countries, a major initiative of the countries was organized in the 18th UN climate change conference in Doha, Qatar in 2012 (Klemes et al., 2012). From the different studies conducted in this regard, rapid urbanization and population growth, lack of a well-developed urban transit system, high number of personal vehicles, low fuel prices, and traffic congestion were found as the main parameters that should be taken into account more seriously (SAADI, 2011; Elmi and Al-Rifai, 2012). Additionally, it was found that indoor air quality was considered much less than that of ambient air quality in the GCC countries (Al-Rashidi et al., 2012; Cohen et al., 2013; Gevao et al., 2007; Yeatts et al., 2012). Worth noting that, Oman, Kuwait, Bahrain, Qatar, Saudi Arabia, and the UAE formed GCC in March 1981 to promote stability and cooperation in the region. Some basic information about the GCC countries is summarized as shown in Table 1.

1.1. Types of air pollutants

Air pollutants, which may cause environmental health risk (Willis et al., 2010; Al-Wahaibi and Zeka, 2015), are categorized in a number of different ways. The composition of air pollutants and their associated toxicity vary in different settings (Baawain and Al-Serihi, 2014). Millions of people suffer from preventable chronic respiratory diseases worldwide because of air pollution. Such respiratory diseases could result in a major public health challenge in both developing and developed countries due to their frequency and economic impact, through increased health care expenses and lost disability adjusted life years (Aït-Khaled et al., 2001). Deaths due to the economic burden of air pollution cost the global economy about US$ 225 billion in lost labor income in 2013 (World Bank, 2016). According to the World Bank and the Institute for Health Metrics and Evaluation predict, an estimated 125,000 lives were lost in the Middle East and North Africa countries because of diseases associated with outdoor and indoor air pollution in 2013, which result in human suffering and reducing economic development. When looking at fatalities across all age groups through the

Table 1
Some basic information about the GCC countries obtained from GCC Statistical Center (2016).

GCC country	Area[a]	Population	GDP	GDP	GNI[a]	CO_2 emissions[a]
	km^2 in 2017	#	Million USD	Per capita USD	Per capita in USD in 2016	Metric tons per capita in 2014
UAE	83,600	9,121,167	348,744	38,234.54	40,480	23.302
Bahrain	771	1,423,726	32,179	22,602.20	NA	23.450
KSA	2,149,690	31,742,580	644,936	20,317.68	21,720	19.529
Oman	309,500	4,414,051	66,824	15,139.03	NA	15.443
Qatar	11,610	2,617,634	152,452	58,240.46	NA	45.423
Kuwait	17,820	4,132,415	109,674	26,540.02	34,890	25.224

[a] Data from World Bank website.

welfare losses, the aggregate cost of premature deaths attributable to air pollution was about 2.2% of regional gross domestic product (GDP). Since the economy of the GCC countries has grown in the recent decades, environmental challenges and issues raise too. The suggested way to sustain the achievements and further improvement in the quality of life is to integrate a better environment as only through such integration the GCC countries can shift towards the economy of the future.

The most important air pollutants are carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), nitrogen oxides (NO_x), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), persistent organic pollutants (POPs), ozone (O_3), and sulfur dioxide (SO_2). In the US, many of these pollutants are called as "criteria" air pollutants, because maximum allowable concentrations have been set in the National Ambient Air Quality Standards (NAAQS) based on the human health and/or environmental criteria.

1.2. Standards and regulations

In 2016, the US Environmental Protection Agency (USEPA) modified NAAQS for the pollutants considered in this study (Table 2). Standards with different time durations have been defined, because for some pollutants like CO, short-term effect is a concern, while for PM long-term effect is more important. WHO has provided additional guidelines, while they are not compulsory for governments to follow (Han and Naeher, 2006). Similar rules have been followed by other national and international organizations, such as EU, Occupational Safety and Health Administration (OSHA), Omani Ambient Air Quality Provisional Standards (OAAQPS), and so on. Comparing between the GCC and the international standards reveals that the GCC values are relaxed. For example, EPA has set a limit of 150 μg m^{-3} for daily PM_{10}, three times higher than the WHO guideline, while OAAQPS and KUEPA have set 150 and 350 μg m^{-3} as daily regulation limits, respectively. The guideline values for the selected air pollutants in other standards are presented in Table 2.

To the best of the authors' knowledge, systematically monitoring air pollutants in the GCC countries is poor. In other words, the comprehensive and accurate measurement of the air pollutants is in its minimum level. Besides, the resulted values are normally compared with the standards in the developed countries. This would be acceptable; however, the values should be adjusted according to the local conditions (meteorological and environment conditions). Such initial steps are needed all over the GCC countries in the long term. Although some governments have developed some strategic plans or even specific guidelines in the recent years, further steps are still needed. For example, the Ministry of Environment and Climate Affaires (MECA) of Oman has a responsibility on 10 air monitoring stations across the country. More than 14 monitoring stations in different locations throughout Abu Dhabi and Dubai (UAE) are being utilized for air monitoring purposes (Al-Jassmi, 2013; Pierson and Heaton, 2014). However, the absence of regular maintenance may result in poor and/or even unreliable air quality information. Therefore, due to the lack of scientific regulations, academic studies and policy recommendations are faced with some difficulties.

1.3. Objectives

In recent decades, public concern about deteriorating air quality and its associated impacts has grown significantly. However, very little information has been published to assess the concentration of air pollutants in hot and arid/semiarid regions. This kind of climate may be interesting to study; because, compared to cold climate, hot climate may have a strong impact on chemical reaction rates, degradation reactions, microbial activities, and so on. Therefore, this review study aimed to 1) critically discuss the current situation of air quality and explore the knowledge gaps on ambient air quality in the GCC countries, and 2) discuss the strategies and policies for clean air quality in the GCC countries. To achieve the following objectives, available studies, included scientific reports, conference papers, institutional/governmental reports and similar studies (since early 2000) were reviewed. Further, similar topics that considered results from receptor models, source apportionment studies and emission inventories were also included.

2. Air pollution assessment

The ecological impacts, such as desertification, water scarcity, and air and water pollution are likely to be higher in the GCC countries than that of other parts of the world. Furthermore, the rapid increase in population, industrial development, and wasteful consumption of resources have been deteriorated the air quality in the region (Reiche, 2010). Moreover, due to the small land area of some countries in the GCC countries compared to the neighboring countries, such as Qatar, UAE, and Kuwait, it is difficult to determine unambiguously, which pollutants originate from inside and which are from outside of the country. Therefore, to achieve mutual goals and to protect public health and the environment, additional efforts to assess air quality are needed.

Table 2
Air quality guidelines and standards (μg m^{-3}).

Source in μg m^{-3}	NO_2		PM_{10}		$PM_{2.5}$		SO_2			CO		O_3	
	1 yr	1-h	1 yr	24-h	1 yr	24-h	3-h	24-h	1 yr	1-h	8-h	1-h	8-h
WHO (2005)	40 (20)[a]	200 (100)[a]	20	50	10	25		20 (7)[a]		30,000 (24.3)[b]	10,000 (8.1)[b]		100 (47)[a]
NAAQS (2016)	100 (50)[a]	200 (100)[a]		150	12	35	1410 (500)[a]		75 (27)[a]	43,200 (35)[b]	11,100 (9)[b]		148 (70)[a]
EU	40 (20)[a]	200 (100)[a]	40	50	25		350[c] (124)[a,c]	125 (44)[a]			11,500 (9.3)[b]		120 (56.8)[a]
California	60 (30)[a]	365 (180)[a]	20	50	12	35	705[c] (250)[a,c]			24,700 (20)[b]	11,100 (9)[b]	190 (90)[a]	148 (70)[a]
Omani Ambient Air Quality Provisional Standards 41/2017 (OAAQPS)	130[d] (64)[a,d]	250 (123)[a]		150		65	350[c] (124)[a,c]	150 (53)[a]		30,000 (24.3)[b]	10,000 (8.1)[b]		120 (56.8)[a]
KUEPA, residential[e]	67 (33)[a]	225 (110)[a]	90	350			444[c] (157)[a,c]	157 (56)[a]	80 (28)[a]	34,000 (27.6)[b]	11,500 (9.3)[b]	157 (74.3)[a]	120 (56.8)[a]
KUEPA, industrial[e]	67 (33)[a]	225 (110)[a]	90	350			783 (278)[a]	523 (185)[a]	157 (56)[a]	34,000 (27.6)[b]	11,500 (9.3)[b]	157 (74.3)[a]	120 (56.8)[a]

Blank spaces indicate not detected/reported data.
[a] ppb.
[b] ppm.
[c] 1-h basis.
[d] 24-h basis.
[e] Kuwait Environment Public Authority (2001).

2.1. Carbon

The rapid growth in many aspects of development in the GCC countries has heavily contributed to the increase of carbon emissions. The GCC countries are facing environmental threats because they depend primarily on fossil fuels and their economies are reliant on the related industries, such as oil, gas, and petrochemical, a main cause of greenhouse gas (GHG) emissions (Abdul-Wahab et al., 2015a, 2015b; Al-Shidi et al., 2016; Lanouar et al., 2016). All the GCC countries, on a global scale, fall in the top 25 countries responsible for the highest GHG emissions per capita (Raouf, 2008; IEA, 2012; Lanouar et al., 2016). For example, only 0.6% of the world populations lived in the GCC countries, but the region contributed 2.4% of the GHG emissions (Reiche, 2010). Oman had the lowest carbon emission per capita in 2010 among the GCC countries, while Qatar and Kuwait had the highest. In case of CO_2, the GCC countries emitted more than four times that of the world's average per capita (IEA, 2012). Additionally, the lack of arable land and water resources prevent the development of forests and green belts as carbon sinks, which may further increase the exposure of the countries' residents to the effects of climate change (Harder and Gibson, 2011).

Carbon emission showed the significance of environmental threats in the GCC countries for several years (Abdul-Wahab et al., 2015a, 2015b). The carbon emission in the UAE was reported as 10.5 ton-carbon-equivalent (TCE) per capita per year, at least twice of the developed countries. Fairly low energy cost and high economic growth resulted in an average emission growth rate of 4.9% annually in UAE (Kazim, 2007). Qader (2009) ascertained that Qatar and UAE has significantly contributed to global CO_2 emissions a result of energy extraction for oil drilling and electricity production. Moreover, the contribution of transportation sector in GHG emission as one of the highest energy-consuming sectors is significant (Al-Sabbagh et al., 2013; Amoatey and Sulaiman, 2017). The road transport sector approximately produced 100% of the CO_2 emissions and 11.7% of the total emissions (PMEW, 2012). Transportation mostly relies on personal vehicles in the GCC countries; however, a few number of studies have considered CO and CO_2 emissions in the GCC countries (Table 3). Normally high concentration of CO occurs in the areas with heavy traffic intensity and industrial zones. Thus, the concentration level of CO is very important in traffic-related exposure studies and epidemiologic investigations.

Although, personal exposures to CO emission seem higher in developing countries than that of the developed countries, the regulated values set by some of the GCC governments are similar to the international guidelines. As shown in Table 2, the reported standards for CO exposure in 1-h and 8-h in the GCC countries are relatively equal to the USEPA and WHO standards. Considering the motorization rate (as discussed later) and rapid industrialization and economic growth, the set values seem unreachable. Therefore, a detailed and accurate assessment is demanded in this region.

In recent years, addition of biofuels to diesel engines has been suggested to mitigate many unfavorable pollutants. The benefits of biofuels on GHG emissions are especially significant, because CO_2, as a main compound in GHG emissions, released from biofuel combustion is offset by the CO_2 captured by the plants from which biodiesel is produced (Barabas et al., 2010). Although implementation of biodiesel fuels is suggested, especially for heavy-duty vehicles, the application of biofuels in the GCC countries is not well developed and related studies have been found rarely.

2.2. PMs and their associated metals

PMs are a serious risk factor for cancer, predominantly respiratory and cardiovascular systems (Pope and Dockery, 2006; Denholm et al., 2016). For example, PMs generated from combustion processes, especially diesel engines (Munir et al., 2013), are more potent in posing adverse health effects than those from the non-combustion processes. PMs refer to particles or droplets are commonly classified as coarse (aerodynamic diameter, 2.5–10 μm), fine (<2.5 μm) and ultrafine (<0.1 μm) PM. $PM_{2.5}$ is more related to transportation sector, while PM_{10} is more related to other particulates, such as air born particulates, etc. (Han and Naeher, 2006). As the size of PMs reduced, their damage became more dangerous (Harrison and Yin, 2000). The WHO guidelines indicate that by reducing PM_{10} concentration from 70 to 20 μg m^{-3}, air pollution-related deaths can be reduced by roughly 15%.

Among common air pollutants, the concentration level of PM is currently under rigorous investigation in the GCC countries. Selected sites were located mainly in Saudi Arabia and Kuwait, as listed in Table 4. The literature reviews clearly indicated the high amount of PMs in the GCC countries (Lanouar et al., 2016). A study by Brown et al. (2008) revealed that annual PM concentration levels in the central site of Kuwait were well above the annual WHO regulations for PM_{10} and $PM_{2.5}$ (see Table 2) by a factor of six and five, respectively. Moreover, daily PM_{10} and $PM_{2.5}$ concentration levels exceeded the daily WHO guidelines by 71% and 59%, respectively. The concentration levels of PM_{10} and $PM_{2.5}$ in Kuwait were found to be high even without considering the sandy storm days (115 and 43 μg m^{-3}, respectively). There were different studies that showed PM concentration levels in Saudi Arabia exceeded the air quality standards (Munir et al., 2013; Habeebullah, 2014, 2016; Habeebullah et al., 2015). For example, the concentration levels of PM_{10} and $PM_{2.5}$ in Jeddah, Saudi Arabia, were exceeded the EU air quality standard in >85% of the samples (Khodeir et al., 2012). However, only 10% of PM_{10} and 18% of $PM_{2.5}$ samples were exceeded the US 24-h standard values (150 and 35 μg m^{-3}, respectively). Al-Ghamdi et al. (2015) reported the TSP concentrations for three different sites in Jeddah, Saudi Arabia. The TSP concentrations were 435, 396, 232 μg m^{-3}, which reflected the contribution of crustal dust components in the collected PMs in 2013. In other studies, the air quality of the Riyadh city, Saudi Arabia classified from good to hazardous for $PM_{2.5}$ and from good to very hazardous for PM_{10} (Rushdi et al., 2013; Al-Harbi et al., 2014). The observed concentration of $PM_{2.5}$ in Qatar was reported more than that of the recommended target by the international standards and regulations (Engelbrecht et al., 2009). In UAE, the environmental agency of Abu Dhabi reported that the maximum PM_{10}

Table 3
CO and CO_2 emissions from different locations in the GCC countries.

Country	Site	Year	CO (ppm)	CO_2 (ppm)	Period	Reference
Bahrain	Five locations	2007	0.5 ± 0.4		Seasonally	Khamdan et al. (2009)
Kuwait	Fahaheel	2004–5	6.7		1-h	Al-Salem and Khan (2008)
	Al-Riqa		0.7			
Kuwait	School at Hawalli	2006	2.6	402	24-h	Al-Bassam et al. (2009)
Kuwait	Jahra	2001–4	0.7–1.9	348–359	1-h	Ettouney et al. (2010)
	Umm Al-Hyman		0.4–0.8	360–362		
Oman	Near a roadway intersection	2003	3.9–10.8		1-h	Abdul-Wahab (2004)
Saudi Arabia	Makkah	2002–3	1.2–1.8		1-h	Al-Jeelani (2009)
Saudi Arabia	Three locations around the Haram Mosque in Makkah	2009	3.0		Average monthly	Al-Jeelani (2013)
			3.7			
			0.5			
Saudi Arabia	Makkah	2011–2	Mean 1.1		Urban 1-h	Munir et al. (2013)

Table 4
Comparative concentrations of PM in different sites in the GCC countries.

Country	Site	Year	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	$PM_{2.5}/PM_{10}$	Period	Reference
Bahrain	Five locations	2007	51 ± 38	181 ± 168	0.3	Seasonally	Khamdan et al. (2009)
Kuwait	North, Central, and South	2004–5	53	130	0.4	12- and 18-month study	Brown et al. (2008)
Kuwait	Two urban and one desert	2004–5	31 to 38	66 to 93	0.4–0.5	period	
Kuwait	20 points in the southern part of Kuwait	2005		From 40 to 91		Monthly	Ramadan, 2010
Kuwait	Jahra	2001–4		155–224		1-h	Ettouney et al. (2010)
	Umm Al-Hyman			110–163			
Oman	Sohar highway	2014–5	21 ± 10			1-h	Nawahda (2015)
Qatar	Qatar	2013	93	168	0.6		Qatar Statistics Authority (2013)
Qatar	Qatar	2006–7	67	165	0.4	1 in 6 day, 24-h for 1-yr	Engelbrecht et al. (2009)
Saudi Arabia	Jeddah			80		1-h	El-Assouli et al. (2007)
Saudi Arabia	Jeddah	2011	28 ± 25	87 ± 47	0.3	Monthly	Khodeir et al. (2012)
Saudi Arabia	Makkah	2011–2		Mean 175		Urban-hourly	Munir et al. (2013)
Saudi Arabia	Three locations around the Haram Mosque in Makkah	2009	73	282	0.3	Average monthly	Al-Jeelani (2013)
			82	166	0.5		
			51	209	0.2		
Saudi Arabia	Makkah	March 2012 to February 2013		196		Annually	Habeebullah, 2014
Saudi Arabia	Taif	2011	47 ± 15	46 ± 31	1.0	24-h	Shaltout et al. (2013)
Saudi Arabia	Riyadh	June 2006	104 ± 61	180 ± 125	0.6	Monthly	Rushdi et al. (2013)
		November 2006	76 ± 66	146 ± 112	0.5		
		February 2007	125 ± 70	268 ± 165	0.5		
		May 2007	189 ± 82	312 ± 147	0.6		
Saudi Arabia	Riyadh	2010–1		576		Average monthly	El-Mubarak et al. (2014)
Saudi Arabia	Makkah	2012–3	144	233	0.6	Annually	Habeebullah (2016)
UAE	Al Mirfa and Abu Dhabi	2007–9		150		24-h	Al-Katheeri et al. (2012)
UAE	Abu Dhabi	2010		129 to 203		24-h	EAD (2013)

concentrations were 10 times higher than the WHO standards, while the peak value was 14 times higher than the limits during dust storms in 2013.

The most recent studies revealed that not only the PM concentrations are important, but also metallic elements, such as S and Pb (Birmili et al., 2006), inorganic compounds (Schlesinger and Cassee, 2003; Schlesinger, 2007) and carbonaceous PM components (Mauderly and Chow, 2008; Omidvarborna et al., 2016) are important. This is very important, since public transportation is not well-developed and transportation mostly relies on personal vehicles in the GCC countries (Amoatey and Sulaiman, 2017). A study on elemental analysis in Jeddah, Saudi Arabia revealed that the largest elemental contributors to the $PM_{2.5}$ mass (36.5% of $PM_{2.5}$ mass) were S and Si, followed by Al, Fe, and Ca. However, the largest contributors to the PM_{10} mass (36.4% of PM_{10} mass) were Si and Ca, followed by S, Al, and Fe (Khodeir et al., 2012). Specific compounds, such as Pb, were observed in the $PM_{2.5}$ after leaded gasoline phase–out (Aburas et al., 2011). High concentration level of S and Ni on $PM_{2.5}$ and PM_{10} was reported from combustion of fossil fuels in Riyadh City (Rushdi et al., 2013). The high concentration level of Al > Fe > Zn > Ni > Pb > Cd in Kuwait confirmed the outcome of recent industrialization, meteorological conditions in Kuwait's arid environment besides soil dusting, saltation, and sea-spray sources (Bu-Olayan and Thomas, 2012). A case study in Sohar industrial estate and Falaj Al-Qabail village, Sultanate of Oman, revealed a large amount Cu and Mn in PMs near Cu industrial processes and reinforcement steel plant (Abdul-Wahab, 2012).

The studies on the released elements in the GCC countries were not conclusive. Additionally, the potentially hazardous elements in the GCC countries were not under control and could be detected above the limits defined by international guidelines. Therefore, continuous monitoring studies are recommended to minimize the impact of the elements in the GCC countries. Moreover, from Table 4, it can be understood that studies on the concentration levels of PM in the GCC countries are more under attention; however, they mainly rely on case studies (Abdul-Wahab, 2006; Abdul-Wahab et al., 2012; Al-Khadouri et al., 2015). This review study also disclosed that PM monitoring in few sites, such as Bahrain and Oman, could not provide precise data for further analysis.

2.3. Nitrogen oxides

In the atmosphere, NO_x, a group of highly reactive gases includes mainly NO_2 and nitric oxide (NO), come from primary (directly from emission sources) and secondary sources (chemical reactions). In the atmosphere, NO_x molecules are highly reactive with other chemicals to form PM and ozone. NO_x molecules interact with oxygen, water and other chemicals to form acid rain. The impact of meteorological data on the reduction level of NO_x is important. Because the formed NO_2 in the atmosphere can be oxidized to HNO_3 by moisture, thereby it reduces the concentration level of NO_x. Short-term exposure to NO_x may cause airway responsiveness and lung function injury, while long-term exposure may reduce immunity and lead to respiratory infections (Al-Salem and Khan, 2010).

The concentration levels of NO_x are currently under extensive investigations, because NO_x emission is well known as one of the main vehicle-related air pollutants (Omidvarborna et al., 2015b) and precursors forming photochemical smog (together with VOCs). As shown in Table 5, UAE and Saudi Arabia are the countries with the highest NO_x concentration level compared to other countries in the GCC countries.

In the GCC countries, the concentration levels of NO_x were assessed commonly based on vehicle exhaust emissions. For example, the maximum hourly concentration of NO_x was reported around 710 ppm (daily average 375 ppm) around the Al-Batinah highway near Sohar city, Oman (Chaichan and Al-Asadi, 2015). A high level of NO_x was also reported from vehicles and traffics close to the busy area of Fahaheel, Kuwait (Khan and Al-Salem, 2007) and the industrial sites of Jeddah City, Saudi Arabia (Hassan et al., 2013), which were exceeded from the international air quality standards. As confirmed by Pierson and Heaton (2014), 24-h average NO_x concentration level was exceeded the standards in downtown Abu Dhabi during 2010 to 2012. According to a survey conducted by Lelieveld et al. (2009), the main prominent NO_x emission sources were from transport, international shipping, power generation and industry. No studies were conducted to

Table 5
NO_x emissions in the GCC countries in Gg NO_2 y^{-1} (Lelieveld et al., 2009).

	Power generation	Residential biofuel use	Transport	Industry	Biomass burning	Total
Bahrain	25	1	24	19	–	69
Kuwait	62	–	54	22	–	138
Oman	24	1	28	6	–	59
Qatar	75	–	22	14	–	111
Saudi Arabia	169	4	625	149	8	955
UAE	82	1	853	35	–	971

evaluate/model the concentration levels of NO_x in Qatar (Al-Naimi et al., 2015), while atmospheric pollutants in the state of Qatar have been released mainly from industrial (flaring and fugitive) and vehicular emissions. Table 6 summarized some of the conducted works in the GCC countries on NO_x emissions so far. Since transportation in the GCC countries relies on vehicles, application of post-treatment technologies to reduce NO_x emission is mandatory.

2.4. SO_2

SO_2, a harmful pollutant to human health, is formed primarily from the combustion of sulfur-containing fuels. SO_2 is usually trapped in the lower atmospheric layer, which allows it to be detected easily at the ground level. In the GCC countries, SO_2 was reported as the largest portion of discharged gases into the air by refineries (Al-Jahdali and Bisher, 2008), electrical power plants and water desalination plants (Al-Rashidi et al., 2005). Al-Rashidi et al. (2005) reported that SO_2 emissions from the existing power plants in Kuwait exceeded the KUEPA standard by 600 μg m^{-3}. In 2007, the concentration level of SO_2 near Manama, Bahrain was reported as 90 μg m^{-3} (Khamdan et al., 2009). At the same time, during 2007–2009, the average hourly concentration of SO_2 near a power plant in Al-Mirfa (Abu Dhabi, UAE) was reported as 300 μg m^{-3} (Al-Katheeri et al., 2012). High concentration level of SO_2 was reported for the most part of oil refineries in Sohar city, Oman by Charabi and Al-Yahyai (2011).

The literature review revealed that energy, transportation and industrial sectors are the major sources of SO_2 emissions. However, the studies on the concentration levels of SO_2 in the GCC countries were mainly focused on the emissions from either refineries or power plants. A summary of SO_2 emission studies in the GCC countries is listed in Table 7.

2.5. Ozone

Ozone, a harmful pollutant to air quality outside of the ozone layer, plays a major role in atmospheric oxidation and formation of urban smog. Ozone is called a secondary air pollutant and it is generated via chemical reactions between NO_x and VOC in the presence of sunlight (Lelieveld et al., 2009). Ozone concentration level is mainly associated with the emissions from industries and vehicle exhausts. Breathing ozone can be dangerous for children, the elderly, and other people who suffer from lung diseases, such as asthma (USEPA). Although there is no common agreement about the critical level of ozone, environment agencies agreed that exposure to 70 and 120 ppb of ozone for 8-h and 1-h may constitute health hazards to human health, respectively NAAQS (2016). The studies in the GCC countries on ozone are very inadequate. A study in Kuwait showed that inhabitants of Fahaheel and Al-Riqa areas were exposed to high level of ozone (154 units more than the limit) in 2005; however, compared to the last year, the ozone concentration level was reduced by >50% (Al-Salem and Khan, 2008). In 2011, the ozone concentration level (8-h) was exceeded compared to the air quality standards at all monitoring stations in UAE (Pierson and Heaton, 2014). Table 8, summarized the limited reports on the concentration level of ozone in the GCC countries.

2.6. Other pollutants

VOCs are a class of air pollutants that are mainly released from fuel-related activities, such as gasoline and diesel-fueled vehicles (Al-Ghamdi et al., 2014), flaring from oil industries, power and desalination plants, fuel storage, biomass combustion, and residential heating systems (Kansal, 2009). The predominant VOCs components in many municipal areas and industrialized zones are BTEX (benzene, toluene, ethylbenzene, and xylene) (Han and Naeher, 2006). Currently >300 different kinds of VOCs were detected by chromatography technique, in which vehicles were found as the major source of BTEX (Al-Ghamdi et al., 2014). Unfortunately, the studies on the concentration level of VOCs in the GCC countries are very rare. Different concentration levels of 48 VOCs were detected in the ambient air of Al-Jahra City, Kuwait that were emitted mainly from oil fields, crude oil production and flaring activities. Among them, the concentration levels of toluene and benzene were exceeded the recommended guidelines by 2% and 19.5%, respectively (Al-Khulaifi et al., 2014). A study by Al-Hamad and Khan (2008) revealed that Kuwait had the highest level of VOCs in ambient

Table 6
Comparative concentrations of NO_x in different sites in the GCC countries.

Country	Site	Year	NO_x (ppb)	Period	Reference
Bahrain	Five locations, Manama	2007	23.8 ± 10.6	Seasonally	Khamdan et al. (2009)
Kuwait	Jahra	2001–4	20.9–97.8	1-h	Ettouney et al. (2010)
	Umm Al-Hyman		19.1–39.9		
Kuwait	Fahaheel	2004–5	170	1-h	Al-Salem and Khan (2008)
	Al-Riqa		85.0		
Kuwait	Fahaheel	2004–5	44.6–80.6	Monthly	Khan and Al-Salem (2007)
Kuwait	School at Hawalli	2006	46.7	24-h	Al-Bassam et al. (2009)
Kuwait	20 points in the southern part of Kuwait	2005	From 7.6 to 16.1	Monthly	Ramadan (2010)
Kuwait	Salmiyah residential area	2008–9	From 6.0 to 108	24-h	Jallad and Espada-Jallad (2010)
Oman	Sohar city	2009	Average 375,375	24-h	Chaichan and Al-Asadi, 2015
Oman	Sultan Qaboos University, Muscat	2014	Allowed average 92.8	1-h	Abdul-Wahab and Fadlallah (2014)
Qatar	Six major intersections along the C-ring road	2012–3	From 38.5 ± 5 to 69.7 ± 4.5	2 weeks period	Al-Naimi et al. (2015)
Saudi Arabia	From power plant and traffic at Al-Taneem, Makkah	2002–3	21.0–56.0	1-h	Al-Jeelani (2009)
Saudi Arabia	Three locations around the Haram Mosque in Makkah	2009	53.5	Average monthly	Al-Jeelani (2013)
			37.1		
			25.5		
Saudi Arabia	Rural area downwind of a desalination plant, Jeddah	2011–2	96.0	1-h	Hassan et al. (2013)
Saudi Arabia	Makkah	2011–2	Mean 25.5	Urban-hourly	Munir et al. (2013)

Table 7
Comparative concentrations of SO_2 in different sites in the GCC countries.

Country	Site	Year	SO_2 ($\mu g\ m^{-3}$)	Period	Reference
Bahrain	Five locations	2007	21.2 ± 15.2	Seasonally	Khamdan et al. (2009)
Kuwait	Al-Jahra	2001	107.7 ± 37.2	Monthly	Al-Rashidi et al. (2005)
	Um Al-Aish		23.3 ± 7.4		
	Rabia		25.0 ± 15.2		
	Mansorya		114.5 ± 26.2		
	Riqqa		90.5 ± 14.5		
	Um Al-Heman		64.0 ± 11.0		
Kuwait	20 points in the southern part of Kuwait	2005	From 13.2 to 16.4	Monthly	Ramadan (2010)
Kuwait	Jahra	2001–4	20.9–38.6	1-h	Ettouney et al. (2010)
	Umm Al-Hyman		27.1–42.9		
Oman	From the 17 stacks of Mina Al-Fahal refinery	May to Aug	31.0 to 44.0	Monthly	Abdul-Wahab (2003)
		Rest of the year	<20.0		
Oman	Sohar highway	2014–5	0–88.9	1-h	Nawahda (2015)
Saudi Arabia	From power plant and traffic at Al-Taneem, Makkah	2002–3	8.0–12.0	1-h	Al-Jeelani (2009)
Saudi Arabia	Three locations around the Haram Mosque in Makkah	2009	32.4	Average monthly	Al-Jeelani (2013)
			8.5		
			11.8		
Saudi Arabia	Makkah	2011–2	Mean 15.8	Urban-hourly	Munir et al. (2013)

air among all other countries in the region. The concentration level of BTEX in the ambient atmosphere of Jeddah, Saudi Arabia was reported as 0.4 ± 0.2 ppb (benzene), 1.4 ± 0.8 ppb (toluene), 0.5 ± 0.3 ppb (ethylbenzene), 1.6 ± 0.6 ppb (m,*p*-xylene) and 0.9 ± 0.4 ppb (o-xylene) during December 2011 to November 2012 (Al-Ghamdi et al., 2014). Although the annual mean concentration level of benzene (0.4 ppb or 1.3 $\mu g\ m^{-3}$) did not exceed the annual threshold limit assigned by the EU level (5 $\mu g\ m^{-3}$), still it might cause a small risk to human health.

Stationary monitoring stations are not able to develop a real concentration map in urban areas, since the concentration level of VOCs from vehicles decreases significantly as the distance from the traffic roads increases. Indeed, VOCs levels were commonly found to have a lower concentration level, even in curbside than that of the middle lanes of the main roads (Han and Naeher, 2006). Therefore, due to lack of data, additional effort is required to develop a map that represents the concentration level of VOCs in the region.

PAHs are a group of environmental contaminants, which are known for their carcinogenic and mutagenic properties (Harrison and Yin, 2000). So far, >100 different PAH components have been detected that are mainly formed during incomplete combustion and/or pyrolysis of organic materials (El-Mubarak et al., 2014). Stationary (industrial and domestic combustion) and mobile sources (road traffic) are also contributed to PAH formation as well (Teather et al., 2013; Omidvarborna et al., 2015a).

Al-Ghamdi et al. (2015) reported that gasoline vehicles (17%), industrial sources (33%), and diesel/fuel oil combustion (50%) were the three major contributors in formation of PAHs in Jeddah, Saudi Arabia. Habeebullah (2013) reported that the total PAH concentration levels in Makkah, Saudi Arabia were ranged between 104 and 195 ng m^{-3}. The PAH concentration levels were 17 to 33 folds higher than that of Al-Ghamdi et al. (2015) study. In another study, El-Mubarak et al. (2014) reported extremely high concentration levels of PAH (up to 1 $\mu g\ m^{-3}$) in Riyadh, Saudi Arabia. Various residential activities and traffic emissions were attributed to such high concentrations (Habeebullah, 2013). Depending on the ambient temperature, VOCs and PAHs are usually adsorbed on the surface of fine and ultra-fine PMs. Thus, characterization of these pollutants and identification of their possible sources will provide insights into strategies to control such pollutants.

In addition, the studies on emerging POPs are very new and definitely limited in the GCC countries (Al-Wabel et al., 2011; Booij et al., 2016). POPs are a group of organic compounds coming from different natural or anthropogenic origins. They are resistant to biodegradation and most of them are carcinogenic compounds. As the POPs are persistent, they are potentially available to migrate into air, water, and soil. They can cause miscarriage, birth defects, health development, or otherwise interfere with the reproduction process. The most common POP pollutants are classified as: ten intentionally produced chemicals, including aldrin, endrin, chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, heptachlor, mirex, toxaphene, hexachlorobenzene (HCB) and polychlorinated biphenyls (PCBs); and two unintentionally produced chemicals, including polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) (Fiedler, 2003). The intentionally produced POPs are further classified as industrial chemicals and organochlorine pesticides, while the unintentionally generated POPs are classified as PAHs, dioxins and furans (El-Shahawi et al., 2010). Such hazardous chemicals are released because of their higher application into agriculture, manufacturing, and solid waste processing industries. A review on the recent studies in the GCC countries revealed that neither the measured concentrations of POPs have been studied nor general guidelines have been presented. To sum up, a systematic approach is needed on the assessment of POPs in this region.

Table 8
Comparative concentrations of ozone in different sites in the GCC countries.

Country	Site	Year	O_3 (ppb)	Period	Reference
Bahrain	Five locations	2007	42.5 ± 22.4	Seasonally	Khamdan et al. (2009)
Kuwait	School at Hawalli	2006	10.1	24-h	Al-Bassam et al. (2009)
			23.7	1-h	
Kuwait	Salmiyah residential area	2008–9	<458	Monthly	Jallad and Espada-Jallad (2010)
Kuwait	Jahra	2001–4	10.5–41.7	1-h	Ettouney et al. (2010)
	Umm Al-Hyman		19.9–46.2		
Oman	Sohar highway	2014–5	1.8–83.4	1-h	Nawahda (2015)
Saudi Arabia	Makkah	2011–2	Mean 26.0	Urban 1-h	Munir et al. (2013)
Saudi Arabia	Three locations around the Haram Mosque in Makkah	2009	37.8	Average monthly	Al-Jeelani (2013)
			22.9		
			32.6		
Saudi Arabia	Jeddah	2011–2	63.5–72.6	Annual	Hassan et al. (2013)

3. Identification of emission sources and air quality modeling demands

3.1. Emission sources

To mitigate the health impacts of the air pollutants, it is important to know the pollutant sources and their contribution (Baawain et al., 2017). The hot and arid/semiarid climate of GCC countries and the lack of rainfall further facilitate the production and transport of aerosols. For example, frequent sandstorms during May–October result in natural pollution. Dust storms could also influence the performance of the alternative energy sources (solar panels), on which frequent studies have been explored recently in the GCC countries (Kazem et al., 2015; Kazem and Chaichan, 2016; Said and Walwil, 2014). Results showed that 48% of the accumulated dusts in the Asian countries were deposited naturally over the solar panels (Menoufi, 2017).

Besides, transportation is a necessity and it is essential for comfortable living in weather like the GCC countries (Elmi and Al-Rifai, 2012). The vehicle in use and motorization rate per 1000 inhabitants of the GCC countries have been increased rapidly as reported by International Organization of Motor Vehicle Manufactures commonly abbreviated as OICA (Table 9). In other words, the average motorization rates in 2015 in the GCC countries were 221% and 85% more than the average values for Asia/Oceania/Middle East and all other countries, respectively. Therefore, in order to devise efficient strategies to mitigate environmental air pollution, source apportionment studies play a major role in research studies. Factor analysis techniques, such as Positive Matrix Factorization (PMF) and Principal Component Analysis (PCA) have been extensively used to perform source apportionment studies (Abdul-Wahab, 2012; Shaltout et al., 2013; Omidvarborna et al., 2014; Al-Ghamdi et al., 2015). For example, PMF analysis has been recognized to be a useful tool in identifying and characterizing major sources of PM (Ross et al., 2005; Al-Olayan et al., 2013). Abdul-Wahab (2004) highlighted the importance of the PCA statistical technique on total suspended particulate (TSP) in Sohar area, since no other study has been reported in this part of Oman. According to Karagulian et al. (2015) study on population-weighted averages for relative source contributions to total $PM_{2.5}$ in urban sites, 52% of $PM_{2.5}$ were from natural sources (dust and soil), 27% from industry, and 12% from transportation sector in Middle Eastern countries. The remaining 9% was unspecific sources of human origins. The most common sources of ambient PM in the GCC countries are summarized as follows (Karagulian et al., 2015; Farahat, 2016):

(1) PM from natural sources, including soil dust (Al-Jeelani, 2013) and sea salt (Bu-Olayan and Thomas, 2012), which are characterized by elements abundant in the earth's crust rocks and the soil. Studies of occupational exposures highlighted that chronic exposure to silica dusts (during dust storms) resulted in lung diseases (Manney et al., 2012; Thalib and Al-Taiar, 2012). Givehchi et al. (2013) reported that the major source of dust was from the deserts of Iraq and Syria.

(2) PM from transportation sector, which normally covers different kinds of PM from different sources, such as exhaust, organic and/or inorganic gaseous PM precursors from the combustion of fuels and lubricants, wear of brake linings, clutch, tires and then re-suspended with crustal or mineral dust particles and road wear materials (Omidvarborna et al., 2014).

(3) PM from industries, a complex category of PMs, mainly from combustion of fossil fuels in various industries, such as power plants, petrochemical, water desalination and even from harbor-related activities (Al-Salem and Khan, 2008; Karagulian et al., 2015).

(4) PM from construction activities (Teather et al., 2013).

According to the source apportionment studies (Table 10), the top three major sources in the GCC countries were commonly categorized as sand dust, construction and industries, and traffic (Khodeir et al., 2012; Elmi and Al-Rifai, 2012; Al-Jeelani, 2013; Al-Olayan et al., 2013). Although epidemiological studies proved that dust particles are not a relevant risk for human health, carbonaceous particles and metals, coming from traffic and industries have been shown huge impact on human health and mortality (Murray et al., 2015).

Although a vast amount of source apportionment analysis has been reported from various geographical locations, source apportionment and monitoring of air pollutants are not systematic (mainly case studies focused on PMs) in the GCC countries (Magram, 2009; Abdul-Wahab, 2012; El-Mubarak et al., 2014). Therefore, it is important to identify the contribution of sources, which are more related to seasonal and/or long-range transport events.

3.2. Air quality modeling

Air quality is dependent on weather condition and is therefore sensitive to climate change. Climate change has been predicted to adversely influence air quality with resulting health effects. Further, frequently target areas impacted by pollutants are not accessible for ambient air monitoring equipment. Thus, computer simulations are needed to predict the required emission reductions and associated costs to offset impacts of climate change on regional air quality. Among the commercial modeling packages, the American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD) and California Puff model (CALPUF) have been used in limited studies in the GCC countries. The major concern of such studies was to estimate the concentration level of local pollutants normally in short term basis (Abdul-Wahab, 2003, 2004; Al-Ghamdi et al., 2015; Al-Naimi et al., 2015; Al-Salem and Khan, 2010; Baawain et al., 2017).

The environmental authorities of Bahrain, Kuwait, and Qatar conducted emission and dispersion modeling studies in recent years (Naber, 2015). The analysis of the results showed that vehicles and power generation were the main sources for PM_{10} and $PM_{2.5}$, while re-suspended dust controlled emission of coarse PMs (>PM_{10}). The major sources of SO_2, NO_x, VOC, and CO emissions were found as industries, refineries, and power generation sectors. The study proposed

Table 9
Number of vehicles in use including passenger cars and commercial vehicles (2010–2015) and motorization rates (2014 and 2015) (OICA, 2015).

Countries/regions	Number of vehicles in use						Motorization rate 2014 (/1000 inh.)	Motorization rate 2015 (/1000 inh.)
	2010	2011	2012	2013	2014	2015		
Bahrain	443	465	489	525	553	578	406	420
Kuwait	1446	1520	1606	1706	1792	1876	477	482
Oman	680	740	810	860	920	980	217	218
Qatar	730	800	870	907	960	1020	442	456
KSA	4870	5280	5703	5950	6240	6600	202	209
UAE	1440	1563	1681	1827	1960	2140	216	234
Asia/Oceania/Middle East	298,552	323,843	351,645	378,796	409,362	436,222	100	105
All countries	1,055,700	1,097,019	1,141,636	1,184,928	1,234,887	1,282,270	178	182

Table 10
Source apportionment studies in the GCC countries.

References	Sources
Ross et al. (2005) In the United Arab Emirates	From the source apportionment studies: most of the fine aerosol mass results from fossil fuel combustion, while mineral dust and local vehicle emissions also contribute to the fine aerosol loading.
Khodeir et al. (2012) In Jeddah City, Saudi Arabia	The $PM_{2.5}$ was dominated by: heavy oil combustion (69%), resuspended soil (8.2%), industrial mix 1 (8.2%), traffic (3.7%), and industrial mix 2 (0.4%). While the PM_{10} mass was dominated by: soil (64%), heavy oil combustion (18%), mixed industrial sources (18%) and marine aerosol (9.3%).
Shaltout et al. (2013) In Taif, Saudi Arabia	Using PCA, three components were detected that can explain 91.5% of the variation in the total data set. Component 1: Reflects the desert dust, whose sampling is unavoidable when collecting $PM_{2.5}$ (72%). Component 2: Related to anthropogenic activities and black carbon (13%). Component 3: The source responsible for high loadings of Cl and moderate loadings of Cu, Zn and BC is hard to identify, but the elements involved suggest another anthropogenic source that could be waste burning (6.5%).
Al-Olayan et al. (2013) In Kuwait City, Kuwait	The estimated contributions to $PM_{2.5}$: sand dust (54%), oil combustion (18%), petrochemical industry (12%), traffic (11%), and from anthropogenic sources transported from outside the country (5%).
Al-Ghamdi et al. (2015) In Jeddah, Saudi Arabia	Three factors of the measured sum of PAH were obtained by PMF: gasoline vehicles (17%), industrial sources, particularly the oil refinery (33%) and diesel/fuel oil combustion (50%).
Karagulian et al. (2015) In Middle Eastern countries	Relative source contributions to total $PM_{2.5}$ in urban sites: natural sources, including dust and soil (52%), industry (27%), traffic emissions (12%), and unspecific sources of human origins (9%).

some of the common challenges across the GCC countries as (Naber, 2015):

- Natural dust (a key pollutant in the region), followed by refineries, power plants, desalination units, transportation (road and shipping).
- Combustion fuels (diesel and heavy oil) lead to NO_2, VOC, and O_3 pollution.
- High sulfur content fuels in the transportation sector (above 2000 ppm in diesel fuels) and power plants.
- Limited or no ambient air quality monitoring stations.
- Absence of a common data assimilation platform and air quality index (AQI) methodology in the GCC countries.

Therefore, several steps (enhancing air quality monitoring network, continuing the modeling exercises, and obtaining raw data necessary for an effective emissions and pollution load assessment) should be undertaken to address air quality at the national and urban scales in the GCC countries. Consideration of air quality impacts on climate change will need increased assurance in model simulations of this effect. Therefore, further work is required to quantify the effect of GCC air quality on climate change.

4. Conclusions and recommendation

Excessive air pollution is often a by-product of unmanageable policies in various sectors. However, in many cases, the reduction of pollution by-products will create a long-term possibility of economic strategies by saving the cost of healthcare services and gaining the benefits on climate funds. This work represents a first attempt to assess available research studies on ambient air quality in the GCC countries.

A careful review of monitoring cases reveals unorganized data with a specific focus on particular areas and/or industries. Moreover, the review study indicated that there is a large contribution from industrial activities, transportation, and dust in the ambient air. Oil related industries and transportation activities are the most important anthropogenic sources in the region. Thus, the GCC governments should introduce more rigorous exhaust emissions tests and regulations on urban transport vehicles and industries. In addition, implementation of treatment technologies, such as catalytic converters, unleaded fuels, as well as alternative fuels are suggested as a solution on improving air quality. Furthermore, there is a need for systematic studies in this region to cover most of the environmental issues. More extensive networks of air quality monitoring stations would allow for more accurate studies and provide a more realistic picture of air pollution sources. In view of this, following recommendations and suggestions would be useful to concerned ministries, universities, non-government organizations and other stakeholders in the region.

- The availability of stringent and updated standards/regulations is an early need.
- Meteorological data gathered must be coherent with pollutant sources designed to be monitored; because, it was found that meteorological data used not in proximity with the pollutants measured.
- More efficient strategies to mitigate air pollution can be followed by focusing on the source apportionment studies.
- Implementation of public transport services, hybrid and biofuel-based vehicles in the transportation sector could get a tremendous gain through emission reduction.
- Air quality modeling studies with continues supports of trustful data in regional scale should be conducted.
- The studies on indoor air quality and networking establishment are limited; therefore, assessment of indoor air quality in the main buildings, such as hospitals, schools, etc., should be continuously carried out.
- It is recommended to assess radon gas emissions since lack of studies on the radon gas is also observed in the literature.
- Finally, related conferences and educational courses in any level should be held and taught in order to enhance the public awareness regarding the environment and air quality.

Future work might be oriented towards the integration of information from more emission inventories, monitoring, modeling and source apportionment studies. Thus, this study is very essential for the GCC or similar countries with comparable climate, as it will assist them to monitor their progress in air quality and help to determine the impact of programs on the future directions.

Abbreviations

AERMOD	American Meteorological Society (AMS)/EPA Regulatory Model
AQI	air quality index
BTEX	benzene, toluene, ethylbenzene, and xylene
CALPUF	California Puff model
CO	carbon monoxide
CO_2	carbon dioxide
DDT	dichlorodiphenyltrichloroethane
GCC	Gulf Cooperation Council
GDP	gross domestic product
GHG	green-house gas
GNI	Gross national income
HCB	hexachlorobenzene
KUEPA	Kuwait Environment Public Authority
MECA	Ministry of Environment and Climate Affaires

NAAQS	National Ambient Air Quality Standards
NO	nitric oxide
NO_x	nitrogen oxides
O_3	ozone
OAAQPS	Omani Ambient Air Quality Provisional Standards
OICA	International Organization of Motor Vehicle Manufacturers
OSHA	Occupational Safety and Health Administration
PAHs	polycyclic aromatic hydrocarbons
PCA	Principal Component Analysis
PCB	polychlorinated biphenyls
PCDD	polychlorinated dibenzo-*p*-dioxin
PCDF	polychlorinated dibenzofuran
PM	particulate matter
PMF	Positive Matrix Factorization
POP	persistent organic pollutants
SO_2	sulfur dioxide
TCE	ton-carbon-equivalent
TSP	total suspended particulate
UAE	United Arab Emirates
USEPA	US Environmental Protection Agency
VOC	volatile organic compound
WHO	World Health Organization

Glossary

$PM_{2.5}$	refers to PM that have a diameter of <2.5 μm.
PM_{10}	refers to PM that have a diameter of <10 μm.
	Flaring particle particles are emitted from a definable point such as a stack.
	Fugitive particle fugitive particles are those not emitted from a definable point such as a stack.

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